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(54) IMPROVEMENTS IN OR RELATING TO PIEZO-ELECTRIC CRYSTAL OSCILLATORS

(71) We, KABUSHIKI KAISHA SUWA SEIKOSHA, a Japanese Company, of 3-4, 4-chome, Ginza, Chuo-ku, Tokyo, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to piezo-electric crystal oscillators and more specifically to piezo-electric crystal oscillators of the kind including a piezo-electric crystal and a complementary MOS field effect transistor amplifier-inverter having at least one stage consisting of a P-channel transistor and an N-channel transistor, said amplifier-inverter having its output drain terminal connected to one terminal of the crystal and its input gate terminal connected to the other crystal terminal and also to said one terminal of the crystal through a feed-back resistor.

The invention seeks to provide improved oscillators of the kind referred to which shall be capable of a relatively wide range of frequency adjustment after manufacture, which shall be of good frequency stability and reliable when in operation, which shall be, to a relatively large extent, free from variations in frequency caused by variations in supply operating voltage or in the circuit elements employed in the oscillators and which shall be such that relatively large tolerances are permissible from the specified electrical dimensions of said circuit elements so that said oscillators will be cheaper than would otherwise be the case.

According to this invention there is provided a piezo-electric crystal oscillator of the kind referred to wherein a fixed capacitor connects to ground that one terminal of the crystal which is connected to the output drain terminal of the amplifier-inverter and a variable capacitor, utilisable for frequency adjustment, connects the other terminal of the crystal to ground.

Said output drain terminal may be connected to said one crystal terminal through an added resistance.

The value of said fixed capacitor and the

value of said added resistance (if provided) are preferably such that, in operation, the phase difference across the crystal is approximately 90°.

The invention is especially advantageously applicable to electronic timepieces and provides improved electronic timepieces wherein the time-standard oscillator is a piezo-electric crystal oscillator as above defined.

The invention is illustrated in and explained in connection with the accompanying drawings, in which:—

Figure 1 is a diagram of a known quartz crystal oscillator employing a complementary MOS amplifier-inverter.

Figures 2 and 3 are explanatory graphical figures.

Figure 4 is a diagram of an embodiment of this invention.

Figure 5 is an explanatory graphical figure related to the embodiment shown in Figure 4, and

Figure 6 shows a modification of the embodiment in Figure 4.

Figure 1 shows a known quartz crystal oscillator utilising complementary MOS field effect transistors, namely a P-channel MOS field effect transistor Trp and an N-channel MOS field effect transistor Trn. The drains Dp and DN of these transistors are connected to a common output drain terminal 2 which is connected back through a feedback resistance Rf to the common gate connecting terminal 1 to which the gates Gp and GN are connected. The quartz crystal vibrator X is also connected between the terminals 2 and 1. A fixed input capacitor C₀ is connected between the gate terminal 1 and ground and a variable output capacitor C₀ which is a frequency regulating capacitor is connected between the drain output terminal 2 and ground.

An oscillator like that shown in Figure 1 has defects which are especially undesirable if the oscillator is used as the time-standard oscillator in an electronic timepiece of high precision. An oscillator for such use must be capable of adjustment of frequency after manufacture. The capacitor C₀ is fixed but

for the purpose of providing for adjustment of frequency the drain capacitance C_D is variable. Because the minimum value C_{Dmin} of the capacitance C_D is relatively large the possible variation of frequency by varying C_D is limited. This is shown by curve A of Figure 2 for which the ordinates are values of frequency and the abscissae are values of capacitance C_D . Maximum and minimum values of C_D are indicated at C_{Dmax} and C_{Dmin} and Δf_D indicates the range of frequency adjustment achievable by varying C_D . As will be seen, this range is relatively small and, accordingly, the circuit elements used in such oscillators—the MOS field effect transistors, the quartz crystal vibrators, the resistances, and the capacitors—must be dimensioned electrically to be in close accord with precisely defined specifications, only small tolerances as regards electrical dimensions being permissible. This requirement is expensive to satisfy for it obviously leads to a high proportion of rejects when manufacturing such oscillators. The curve B of Figure 2 will be referred to later.

Figure 3 shows typical phase/frequency (p/f) and gain/frequency (g/f) characteristics of a quartz vibrator, the curve p being the phase-frequency characteristic and the curve G being the gain/frequency characteristic. If, as in Figure 1, the drain capacitance is used to adjust the frequency, there is necessarily a change of phase difference between the drain output terminal 2 and the gate input terminal 1 the range of phase difference change being in practice from about 90° to about 150° . However, the further the phase difference between the terminals of the quartz crystal departs from 90° , the larger becomes the ratio of variation of frequency to variation of phase and accordingly the internal resistance of the MOS field effect transistors and the characteristic of the inverter are very sensitive to changes in the supply voltage V_{DD} (see Figure 1). This produces relatively large variations in phase difference (Δp) and therefore the stability of the oscillator is adversely affected to a substantial extent. Moreover, because the oscillating condition is caused to depart considerably from the peak of the gain/frequency curve of the quartz crystal, difficulties are experienced in maintaining satisfactory oscillation. The present invention seeks to eliminate or reduce the foregoing defects and disadvantages and does so by varying the value of the input capacitor (instead of that of the output capacitor) to adjust frequency. In this way there is obtained an oscillator which is of substantially improved frequency stability, which has a considerable increased range of the frequency adjustment and which can be designed to ensure that, in all positions of frequency adjustment, the quartz crystal oscillates at or near the peak point of the

gain curve. There is also a higher degree of insensitivity to variations in applied operating voltage and to changes in the circuit elements used.

Figure 4 shows an embodiment of this invention. In Figure 4 it is the input capacitor C_G connected between the gate terminal 1 and earth which is variable, the output capacitance C_D between the drain terminal 2 and earth being fixed. Variation of the capacitance C_G allows of a widened adjustment range of frequency in comparison with what is attainable with an otherwise comparable oscillator as shown in Figure 1, because the minimum C_{Gmin} of the capacitance can be made quite small. This is shown by the curve B in Figure 2 for which capacitance C_G (abscissae) is plotted against frequency f . Minimum and maximum values of C_G are indicated at C_{Gmin} and C_{Gmax} and it will be seen that the range Δf_G of frequency variation achievable is considerably larger than Δf_D .

If the range of frequency variation from the natural frequency f_0 of the quartz crystal vibrator is Δf then the following equation (which is only an approximate equation but near enough true for practical purposes) applies:—

$$\Delta f \approx f_0 \times \left(\frac{1}{C_{Dmin} + C_D} + \frac{1}{C_{Gmin} + C_G} \right) \times \frac{C_0}{2}$$

In this approximate equation C_0 is the equivalent capacitance of the quartz crystal vibrator; f_0 is the natural frequency of the quartz crystal vibrator; C_{Dmin} is the minimum effective drain capacitance if an output capacitance is used as the variable capacitance; C_{Gmin} is the minimum effective gate capacitance if an input capacitance is used as the variable capacitor; and C_D and C_G are respectively the capacitances of variable capacitors which, for the purposes of the above equation, are assumed to be connected respectively to the drains and to gates. The equation serves to compare the case in which the gate capacitance is used to regulate the frequency with that in which the drain capacitance is so used. With a variable drain capacitance the minimum value cannot be permitted to become small enough for the phase difference between the terminals of the crystal (see curve P of Figure 3) to approach too near to 180° and the oscillating condition to get too far off the peak of the gain curve G for otherwise instability of frequency will result. On the other hand, with a variable gate capacitance C_G , a quite low minimum value is permissible regardless of the phase condition. Accordingly, the attainable range of frequency variation attainable is much larger in the case of gate capacitance variation than in the case of drain capacitance variation. This will clearly be seen

from a comparison between curves A and B of Figure 2.

Furthermore, with a known arrangement as in Figure 1 with frequency adjustment effected by the drain capacitance and the gate capacitance fixed, the gain-frequency characteristic curve does not change (see Figure 3), the frequency being varied on the phase/frequency characteristic. With an oscillator in accordance with this invention, with C_0 variable and C_D fixed, the ratio of variation of frequency to variation of phase can be made a minimum by so choosing the value of the fixed capacitance C_D and inserting between the drain terminal 2 and the adjacent terminal 3 of the crystal an output resistance R_0 of such value that a phase difference of about 90° between the terminals of the quartz crystal vibrator is determined. Figure 6 illustrates a modification in which a resistance R_0 is so inserted. Of course in some cases the output resistance R_0 may not be necessary.

Because, with this invention the ratio of frequency change with variation of phase difference can be practically fixed at a minimum, there is much less sensitivity (as compared with the known arrangement of Figure 1) to change in supply voltage or characteristic of the inverter. Moreover, because the frequency is regulated on the gain peak-frequency characteristic curve G_0 shown in Figure 5 when the value of the capacitor C_0 is changed oscillation can be caused to occur at all positions of frequency adjustment at or near the peak of a resonance curve and, of course, the gain of the quartz crystal is a maximum at such a peak. It will be seen from Figure 5 that if the maximum capacitance of the input capacitor connected to the gate terminal is changed from CG_1 to CG_3 , oscillation can be performed within the range between the gain peak points P_1 and P_3 as shown in Figure 5, and thus the condition for most stable oscillating condition can be maintained. Figure 5 shows this by graphically illustrating what occurs with three different values of C_0 , the figure showing three resonance curves CG_1 , CG_2 , CG_3 , to the peaks of which the gain peak frequency curve G_0 is tangential, and three corresponding approximately 90° phase difference curves P_1 , P_2 and P_3 .

The invention is particularly useful for the time standard oscillators of electronic

timepieces for the advantage of good freedom from dependence of frequency upon variations in supply voltage or changes in the threshold voltages of MOS field effect transistors or changes in mutual conductance, is of great importance in such timepieces. Moreover the achievement of a wide range frequency adjustment, with the consequence that wider tolerances from specification can be accepted for the various circuit elements in the oscillator is very advantageous from the viewpoint of reducing cost of manufacture.

WHAT WE CLAIM IS:—

1. A piezo-electrical crystal oscillator of the kind including a piezo-electric crystal and a complementary MOS field effect transistor amplifier-inverter having at least one stage consisting of a P-channel transistor and an N-channel transistor, said amplifier-inverter having its output drain terminal connected to one terminal of the crystal and its input gate terminal connected to the other crystal terminal and also to said one terminal of the crystal through a feed back resistor wherein a fixed capacitor connects said one crystal terminal to ground and a variable capacitor, utilisable for frequency adjustment, connects said other crystal terminal to ground.
2. An oscillator as claimed in claim 1 wherein said output drain terminal is connected to said one crystal terminal through an added resistance.
3. An oscillator as claimed in claim 1 or 2 wherein the value of said fixed capacitor and the value of said added resistance (if provided) are such that, in operation, the phase difference across the crystal is approximately 90° .
4. Piezo-electric oscillators substantially as herein described with reference to Figures 4 and 5 or to Figure 6 of the accompanying drawings.
5. An electronic timepiece having a time-standard oscillator constituted by an oscillator as claimed in any of the preceding claims.

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from a comparison between curves A and B of Figure 2.

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timepieces for the advantage of good freedom from dependence of frequency upon variations in supply voltage or changes in the threshold voltages of MOS field effect transistors or changes in mutual conductance, is of great importance in such timepieces. Moreover the achievement of a wide range frequency adjustment, with the consequence that wider tolerances from specification can be accepted for the various circuit elements in the oscillator is very advantageous from the viewpoint of reducing cost of manufacture.

WHAT WE CLAIM IS:—

1. A piezo-electrical crystal oscillator of the kind including a piezo-electric crystal and a complementary MOS field effect transistor amplifier-inverter having at least one stage consisting of a P-channel transistor and an N-channel transistor, said amplifier-inverter having its output drain terminal connected to one terminal of the crystal and its input gate terminal connected to the other crystal terminal and also to said one terminal of the crystal through a feed back resistor wherein a fixed capacitor connects said one crystal terminal to ground and a variable capacitor, utilisable for frequency adjustment, connects said other crystal terminal to ground.
2. An oscillator as claimed in claim 1 wherein said output drain terminal is connected to said one crystal terminal through an added resistance.
3. An oscillator as claimed in claim 1 or 2 wherein the value of said fixed capacitor and the value of said added resistance (if provided) are such that, in operation, the phase difference across the crystal is approximately 90° .
4. Piezo-electric oscillators substantially as herein described with reference to Figures 4 and 5 or to Figure 6 of the accompanying drawings.
5. An electronic timepiece having a time-standard oscillator constituted by an oscillator as claimed in any of the preceding claims.

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